

LHC signatures for Z' models with continuously distributed mass

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Abstract

We discuss phenomenological consequences of renormalizable Z' models with continuously distributed mass. We point out that one of possible LHC signatures for such model is the existence of broad resonance in Drell-Yan reaction $pp \rightarrow Z' \rightarrow l^+l^-$.

The aim of this note is the discussion of the LHC signatures for renormalizable models with continuously distributed mass proposed in refs.[1, 2]. Note that recent notion of an unparticle, introduced by Georgi [3, 4] can be interpreted as a particular case of a field with continuously distributed mass [1, 2, 5, 6, 7]. Namely, we consider renormalizable models with vector interactions [1, 2]. We point out that one of possible LHC signatures for such models is the existence of broad resonance in Drell-Yan reaction $pp \rightarrow Z' \rightarrow l^+ l^-$.

Consider the Stueckelberg Lagrangian [8]

$$L_0 = \sum_{k=1}^N \left[-\frac{1}{4} F^{\mu\nu,k} F_{\mu\nu,k} + \frac{m_k^2}{2} (A_{\mu,k} - \partial_\mu \phi_k)^2 \right], \quad (1)$$

where $F_{\mu\nu,k} = \partial_\mu A_{\nu,k} - \partial_\nu A_{\mu,k}$. The Lagrangian (1) is invariant under gauge transformations

$$A_{\mu,k} \rightarrow A_{\mu,k} + \partial_\mu \alpha_k, \quad (2)$$

$$\phi_k \rightarrow \phi_k + \alpha_k \quad (3)$$

and it describes N free massive vector fields with masses m_k . For the field $B_\mu = \sum_{k=1}^N c_k A_{\mu,k}$ the propagator in transverse gauge is

$$D_{\mu\nu}(p) = (g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) \left(\sum_{k=1}^N \frac{|c_k|^2}{p^2 - m_k^2} \right). \quad (4)$$

In the limit $N \rightarrow \infty$

$$D_{\mu\nu}(p) \rightarrow (g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) D_{int}(p^2), \quad (5)$$

where

$$D_{int}(p^2) = \int_0^\infty \frac{\rho(t)}{p^2 - t + i\epsilon} dt \quad (6)$$

and $\rho(t) = \lim_{N \rightarrow \infty} |c_k^2| \delta(t - m_k^2) \geq 0$. One can introduce the interaction of the field B_μ with fermion field ψ in standard way, namely

$$L_{int} = e \bar{\psi} \gamma_\mu \psi B^\mu. \quad (7)$$

The Feynman rules for this model coincide with Feynman rules for quantum electrodynamics except the replacement of the photon propagator

$$D_{\mu\nu}^{tr}(p) = (g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) \frac{1}{p^2} \rightarrow (g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) D_{int}(p^2). \quad (8)$$

This generalization of quantum electrodynamics preserves the renormalizability for finite $\int_0^\infty \rho(t)dt$ because the ultraviolet asymptotic of $D_{int}(p^2)$ coincides with free photon propagator $\frac{1}{p^2}$. Note that for $\rho(t) \sim t^{\delta-1}$ we reproduce the case of vector unparticle with propagator $\sim \frac{1}{(p^2)^{1-\delta}}$. For the propagator $D_{int}(p^2) = \frac{1}{p^2} + \frac{1}{(p^2-M^2)}$ we obtain generalization of quantum electrodynamics with additional massive vector field. Consider a model with spectral density

$$\rho(t) = k(t - t_1)(-t + t_2) \quad (9)$$

for $t_1 \leq t \leq t_2$ and $\rho(t) = 0$ for $t \geq t_2$ or $t \leq t_1$. The coefficient k is determined from the normalization condition $\int_0^\infty \rho(t)dt = 1$ and it is equal to $k = \frac{6}{(t_2-t_1)^3}$. For the spectral density (9) the propagator $D_{int}(p^2)$ has the form

$$D_{int}(p^2) = k[-\bar{t}_1\bar{t}_2 \ln \frac{\bar{t}_2}{\bar{t}_1} + \frac{1}{2}(\bar{t}_1^2 - \bar{t}_2^2)], \quad (10)$$

where $\bar{t}_1 = t_1 - p^2$ and $\bar{t}_2 = t_2 - p^2$. Note that in the limit $t_1 \rightarrow t_2$ the spectral density $\rho(t) \rightarrow \delta(t - t_1)$, $D_{int}(p^2) \rightarrow \frac{1}{p^2 - t_1}$ and the model describes interaction of massive vector field with fermions. The propagator (10) of the model does not contain any singularity in p^2 in comparison with $\frac{1}{p^2 - t_1}$ propagator which has singularity for $p^2 = t_1$. The function $|D_{int}(p^2)|$ has a maximum $\sim \frac{1}{t_2 - t_1}$ in comparison with the maximum $\frac{1}{\Gamma m}$ of the propagator $|D_\Gamma(p^2)| = |\frac{1}{p^2 - m^2 - i\Gamma m}|$. Note that the propagator $D_\Gamma(p^2)$ takes into account the finite decay width of vector boson. So vector particle with continuously distributed mass looks like standard vector particle with some internal decay width which is determined by spectral density $\rho(t)$. Consider the second example of the spectral density $\rho(t)$ based on closed analogy with the propagator $D_\Gamma(p^2)$. Namely, approximately the following equality takes place:

$$\frac{1}{p^2 - m^2 - im\Gamma_{int}} \approx \int_0^\infty \frac{\rho(t)dt}{p^2 - t - i\epsilon}, \quad (11)$$

where

$$\rho(t) = \frac{1}{\pi} \frac{\Gamma_{int}m}{(t - m^2)^2 + \Gamma_{int}^2 m^2}. \quad (12)$$

For GUT inspired Z' models [9] the ratio of the total decay width to Z' mass typically is

$O(1)$ percent. For the Z_{SSM} model ¹ the ratio $\frac{\Gamma}{M}$ is the maximal one among GUT inspired models and it is equal to $(\frac{\Gamma}{M})_{SSM} = 0.03$. Typical invariant dilepton mass resolutions for Drell-Yan reactions

$$pp \rightarrow \mu^+ \mu^- + \dots, \quad (13)$$

$$pp \rightarrow e^+ e^- + \dots \quad (14)$$

are 4 percent (for $M_{Z'} = 1 \text{ TeV}$, $\mu^+ \mu^-$, CMS detector [10]) and 2 percent (for $M_{Z'} = 1 \text{ TeV}$, $e^+ e^-$, CMS detector [10]). ² It means that for GUT inspired Z' boson LHC will not be able to measure the decay width of Z' boson. For Z' boson with continuously distributed mass and with internal decay width (12) Γ_{int} bigger than the $e^+ e^-$ or $\mu^+ \mu^-$ invariant mass detector resolutions we can measure the internal decay width Γ_{int} and thus distinguish the model with continuously distributed mass from GUT inspired Z' models. Note that we can modify the Z' model by the introduction of some additional neutral massive fermion ν_M which interacts with Z' boson like $\bar{\nu}_M(g_L \gamma_\mu(1 - \gamma_5) + g_R \gamma_\mu(1 + \gamma_5))Z'_\mu$. For $2M_{\nu_M} < M_{Z'}$ the Z' boson has invisible decays into two neutral leptons ν_M with some decay width Γ_{MM} and for big g_L , g_R the decay channel $Z' \rightarrow \nu_M \bar{\nu}_M$ dominates. This model imitates the effects related with nonzero internal decay width of Z' boson with continuously distributed mass. There are two evident observable effects related with nonzero Γ_{int} for LHC phenomenology. For the Drell-Yan reaction

$$pp \rightarrow Z' \rightarrow l^+ l^- \quad (15)$$

the cross section is

$$\sigma(pp \rightarrow Z' \rightarrow l^+ l^-) = \sigma(pp \rightarrow Z') \cdot Br(Z' \rightarrow l^+ l^-). \quad (16)$$

For the case when Z' boson has additional "internal" decay width $\Gamma_{Z',int}$ we have additional dilution factor in branching due to nonzero $\Gamma_{Z',int}$, namely:

$$Br(Z' \rightarrow l^+ l^-) \rightarrow Br(Z' \rightarrow l^+ l^-) \cdot \frac{\Gamma_{Z'}}{\Gamma_{Z'} + \Gamma_{Z',int}}. \quad (17)$$

¹In the Z_{SSM} model the couplings of Z' boson with quarks and leptons coincide with the corresponding couplings of Z boson [9].

²For the ATLAS detector mass resolutions are similar [11].

Another additional factor that can complicate LHC discovery is that for large $\Gamma_{Z',int}$ the Z' boson becomes rather broad that increases the averaging interval and leads to the increase of Drell-Yan background. Really, for GUT inspired Z' boson the ratio $\frac{\Gamma_{Z'}}{M_{Z'}}$ is rather small typically less than 0.03. For instance, for the SSM model we have $\frac{\Gamma_{Z'}}{M_{Z'}} = 0.03$. For LHC for both CMS and ATLAS detectors dimuon invariant mass resolution for $M_{inv}(\mu^+\mu^-) \geq 1 \text{ TeV}$ is bigger or equal to 3 percent that means in particular that LHC will not be able to measure internal decay widths for GUT inspired Z' bosons. For relatively big $\Gamma_{Z',int}$, say for $\frac{\Gamma_{Z',int}}{M_{Z'}} = 0.1$ and $M_{Z'} = 1.5 \text{ TeV}$ LHC will be able to test internal structure of the Z' resonance. The LHC discovery of broad vector resonance will be an evidence (not proof of course) in favor of internal structure of Z' resonance. As an example consider Drell-Yan production of the SSM Z' boson with $M_{Z'} = 1 \text{ TeV}$. The cross section production for such boson is $\sigma(pp \rightarrow Z' \rightarrow \mu^+\mu^-) \approx 86 \text{ fb}$ [10]. For the Z' boson with internal decay width $\frac{\Gamma_{Z',int}}{M_{Z'}} = 0.09$ the suppression factor is $\frac{\Gamma_{Z'}}{\Gamma_{Z'} + \Gamma_{Z',int}} = 0.25$ and $\sigma(pp \rightarrow Z' \rightarrow \mu^+\mu^-) \approx 21.5 \text{ fb}$. The Drell-Yan cross section which is the main background for the Z' production is estimated to be [10]

$$\sigma_{DY}(pp \rightarrow \mu^+\mu^- | m_{inv}(\mu^+\mu^-) \geq 1 \text{ TeV}) = 6.6 \text{ fb} \quad (18)$$

For the integral luminosity $L_t = 10 \text{ fb}^{-1}$ the number of signal and background events in the dimuon mass interval $m_{inv}(\mu^+\mu^-) \geq 1 \text{ TeV}$ are $N_S = 215$, $N_B = 66$ and the significance [12] $S_c = 2(\sqrt{N_S + N_B} - \sqrt{N_B}) = 17.2$.³ It means that such resonance if it exists will be discovered at LHC at low luminosity stage. Moreover the dimuon resolution for $m_{inv}(\mu^+\mu^-) = 1.5 \text{ TeV}$ is around 4 percent so we can measure the decay width of Z' boson. Note that the use of the Drell-Yan reaction $pp \rightarrow Z' \rightarrow e^+e^-$ with electron-positron pair in final state could be even more promising since the cross sections and the branchings are the same as in dimuon case but electron-positron invariant mass resolution $m_{inv}(e^+e^-)$ is better than in the dimuon case [10]. For instance, for $m_{inv}(e^+e^-) = 1.5 \text{ TeV}$ the electron-positron mass resolution is estimated to be around 2.5 percent [10] that will allow to measure the Z' decay width with better accuracy.

³For integral luminosity $L_t = 1 \text{ fb}^{-1}$ $S_c = 5.4$

Note that Current TEVATRON experimental bound on M is $M \geq 850 \text{ GeV}$ for SSM Z' boson [13]. For the model with large TEVATRON Γ_{inv} bound is much weaker due to dillution factor and broadness of the resonance structure.

To conclude in this note we discussed LHC signatures for Z' models with continuously distributed mass. One of the possible effects due to nonzero internal decay width of Z' is the existence of rather broad resonance structure in Drell-Yan reaction $pp \rightarrow Z' \rightarrow l^+l^-$.

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